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Non-Newtonian fluids through porous media: micro- and macro-scale properties of power-law fluids

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Overview

Introduction: How do non-Newtonian effects impact porous media flows ?

The physic is complex,

- non-linearities,
- memory effects,
- adsorption...

Porous media flow is also complex,

- multi-scale,
- confinement effects...

Polymer flows in EOR,

- increase viscosities,
- reduce instabilities.

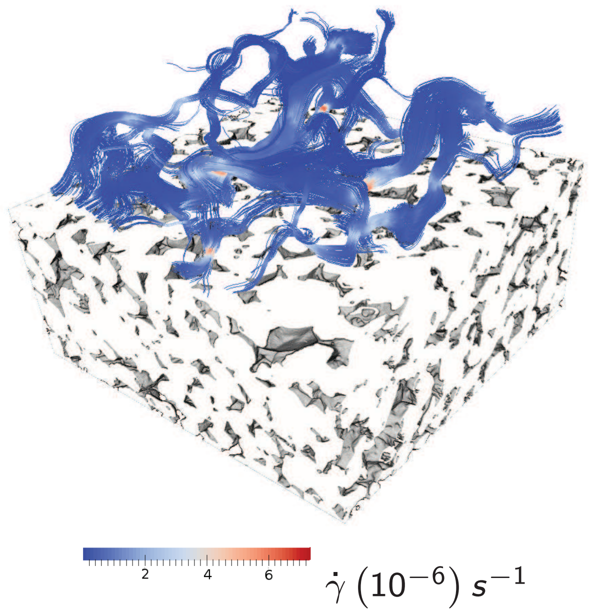


Fig: Power-law fluid flowing through a Bentheimer sandtone

Context

$$\mu = \mu_0 \quad \Rightarrow \quad \langle U \rangle = -\frac{\mathsf{K}\cdot\nabla p}{\mu_0} \quad \Rightarrow \quad \langle U \rangle \propto \|\Delta p\| \quad \Rightarrow \quad ①$$

$$\mu = \mu_\beta \dot{\gamma}^{n-1} \quad \Rightarrow \quad \langle U \rangle = -\frac{\mathsf{K}(\|\langle U \rangle\|)\cdot\nabla p}{\mu_0} \quad \Rightarrow \quad \langle U \rangle \propto \|\Delta p\|^{1/n} \quad \Rightarrow \quad ②$$

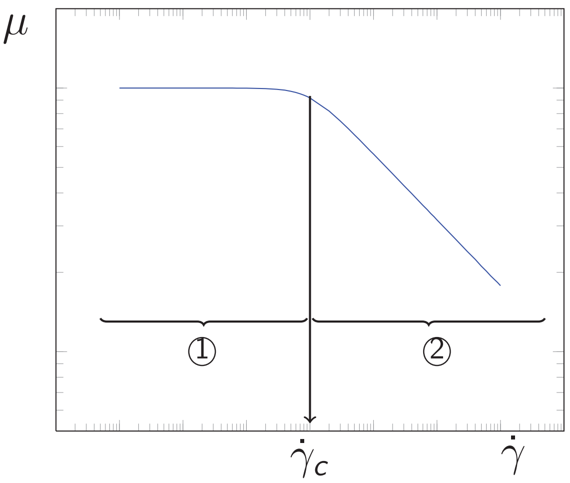


Fig: Non-Newtonian rheology

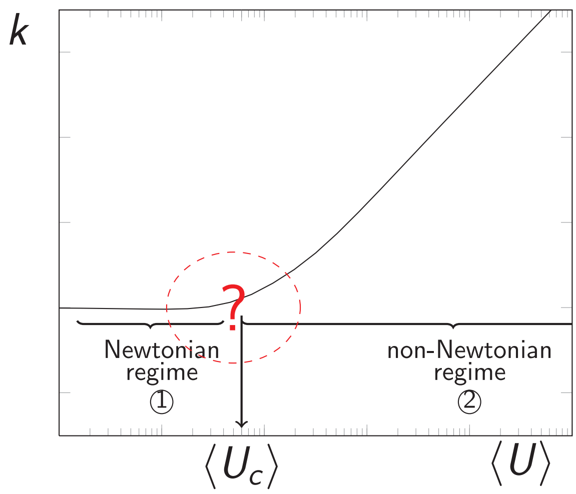


Fig: k versus $\langle U \rangle$

Refs: Auriault et al. 2002; Getachew et al. 1998; Lecourtier et al. 1984; Seright et al. 2011; Sorbie et al. 1991; Zitha et al. 1995

Context

- Literature: $\dot{\gamma}_{eq} = \alpha \frac{4(\langle U \rangle/\phi)}{\sqrt{8k/\phi}}$, Chauveteau 1982.
  Two misunderstood parameters;
  - $R_{\text{eq}} = \sqrt{8k/\phi}$, comes from analogy with a single pipe. Is it still valid in complex multi-scale porous media?
  - α: fitting parameter coming from core-flood experiments. Many hidden physical phenomena (adsorption, time-dependant effects, mass transport)...
- Our Goal: Model only the simplest phenomenon (using plateau + power-law fluid). Can we predict and understand the transition, $\langle U_c \rangle$?

Rheology

- Time-independent fluids, no yield stress. Common models are,
  - plateau + power-law,

$$\mu = \begin{cases} \mu_0 & \text{if } \dot{\gamma} < \dot{\gamma}_c, \\ \mu_0 \left(\frac{\dot{\gamma}}{\dot{\gamma}_c} \right)^{n-1} & \text{else,} \end{cases} \tag{1}$$

  - Carreau,
  - generalized Newtonian.
- Choice of plateau + power-law (and tried others).
- This leads at a macro scale to,

$$\langle U \rangle \propto \begin{cases} \|\Delta p\| \\ \|\Delta p\|^{1/n} \end{cases} \tag{2}$$

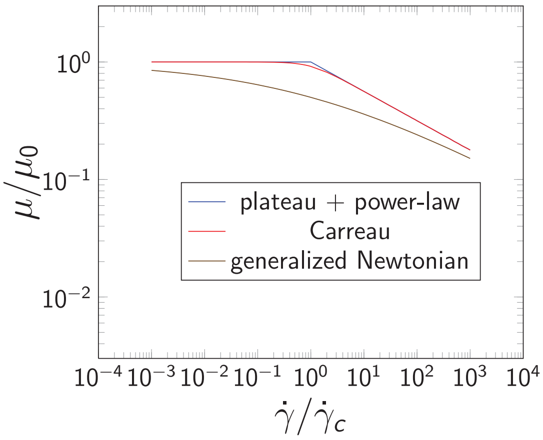
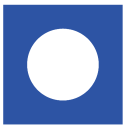
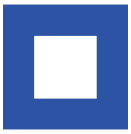
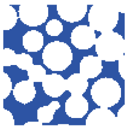


Fig: A few rheological model

Refs: Bird et al. 1968; Collyer 1973; Savins 1969

Porous Media

Keywords: wide panel, isotopic, pore size distribution (PSD).

	1		2	
2D Array name : A		$\phi = 0.72$ $k_0 = 1.1\,10^4$		$\phi = 0.75$ $k_0 = 1.3\,10^4$
3D Packing name : P		$\phi = 0.35$ $k_0 = 33$		$\phi = 0.44$ $k_0 = 46$
3D Bentheimer name : B		$\phi = 0.18$ $k_0 = 1.92$		$\phi = 0.17$ $k_0 = 0.82$
3D Clashach name : C		$\phi = 0.13$ $k_0 = 0.27$		$\phi = 0.14$ $k_0 = 0.48$

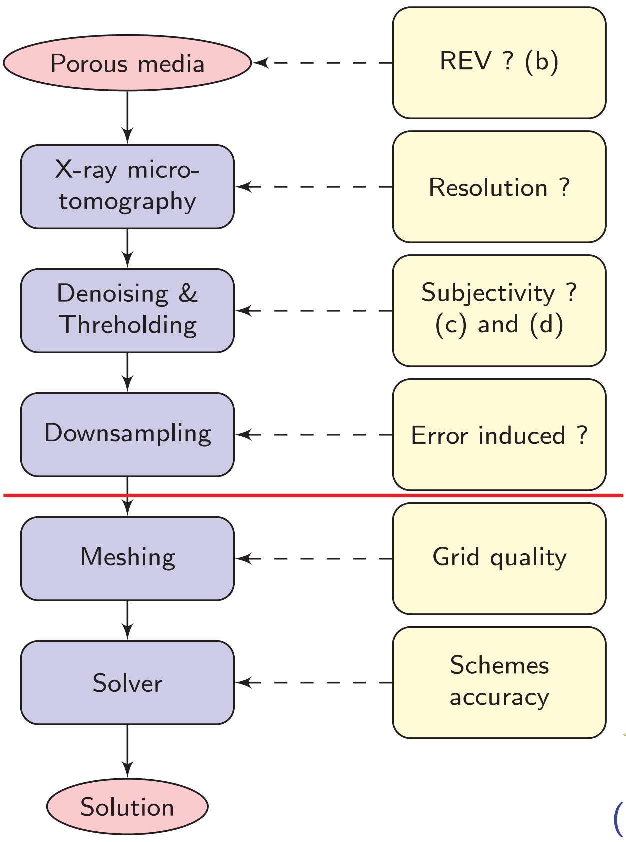
$\phi \searrow$

$k_0 \searrow$

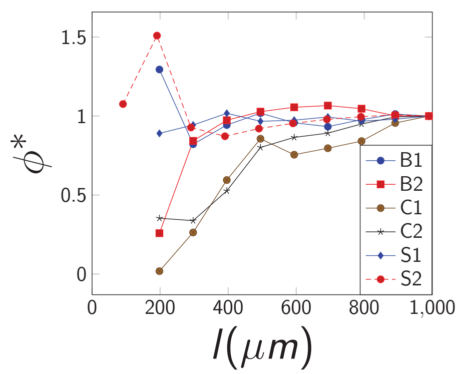
$PSD \nearrow$

Tab: Porous medium investigated (k_0 in Darcy unit, ■ for liquid)

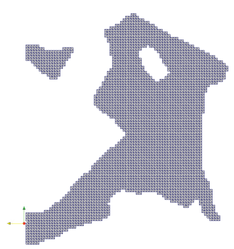
Permeability prediction



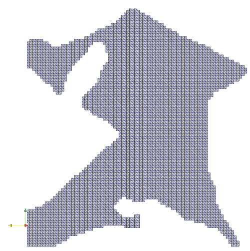
(a) Workflow



(b) ϕ^* versus cube length



(c) Thresholding 1



(d) Thresholding 2

Fig: Permeability prediction issues

Numerical set up

- Equations: $0 = -\nabla p + \nabla \cdot [\nu(\dot{\gamma})(\nabla \mathbf{U} + \nabla \mathbf{U}^T)]$, $\nabla \cdot \mathbf{U} = 0$.
- FVM with OpenFOAM, 2^{nd} order schemes.
- Permeameter, no-slip conditions.
- Grid convergence study, 80 millions meshes, 10^5 hours of CPU time, use of HPC.

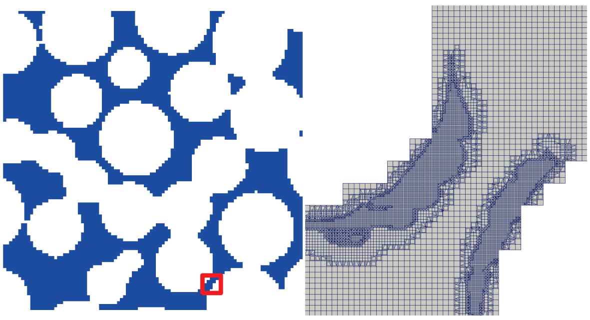


Fig: P1 grid

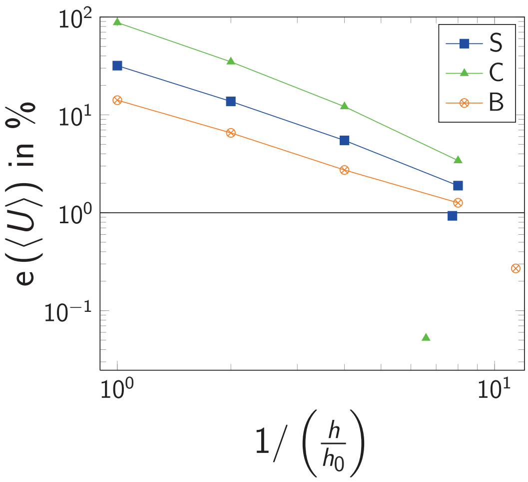


Fig: Grid convergence study

Numerical results - Two regimes

- Relevant dimensionless non-Newtonian number, $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle}$.

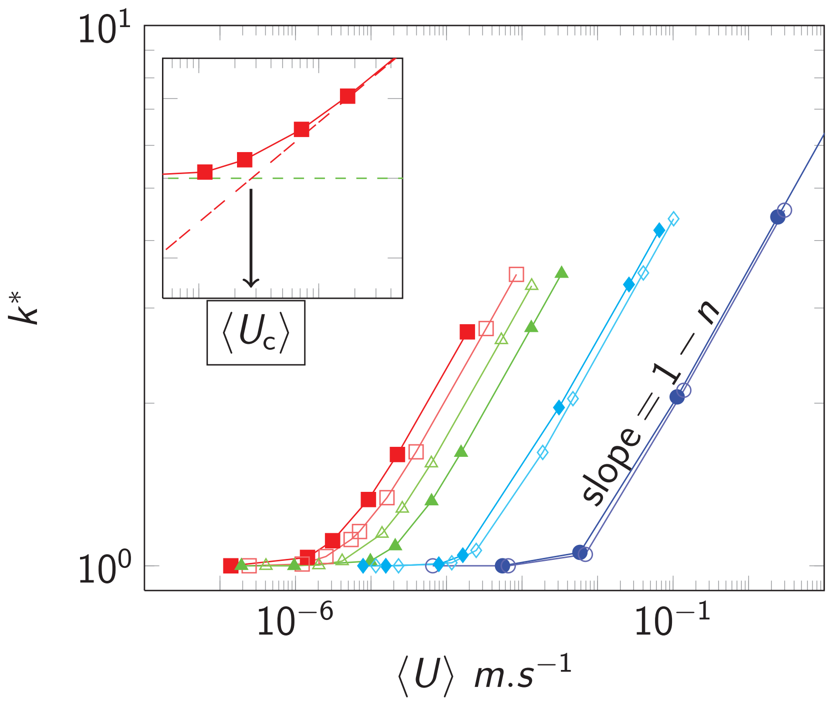


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Rheology: $n = 0.75$ and $\dot{\gamma}_{lim} = 1s^{-1}$.
Medium: A1, A2, B1, B2, C1, C2, P1, P2

Numerical results - Varying n

Varying n: $k \propto \|\langle U \rangle\|^{1-n}$ is equivalent to $\langle U \rangle \propto \|\Delta p\|^{1/n}$.

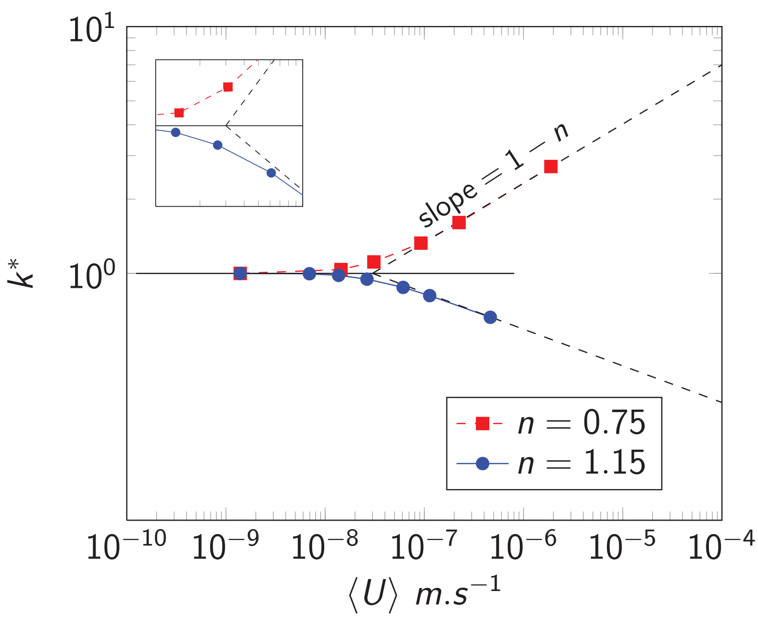


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing $\dot{\gamma}_c$ and varying n.

Numerical results - Varying $\dot{\gamma}_c$

Varying $\dot{\gamma}_c$: $\langle U_c \rangle \propto \dot{\gamma}_c$. This leads to, $\boxed{\langle U_c \rangle = \phi \times \dot{\gamma}_c \ell_{eff}}$.

- Rheology: embedded in $\dot{\gamma}_c$.
- Topology: embedded in ℓ_{eff}.
- Use of ϕ.

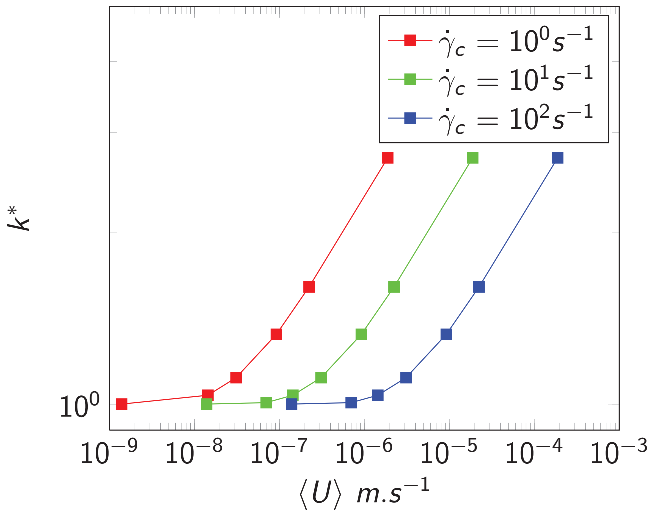
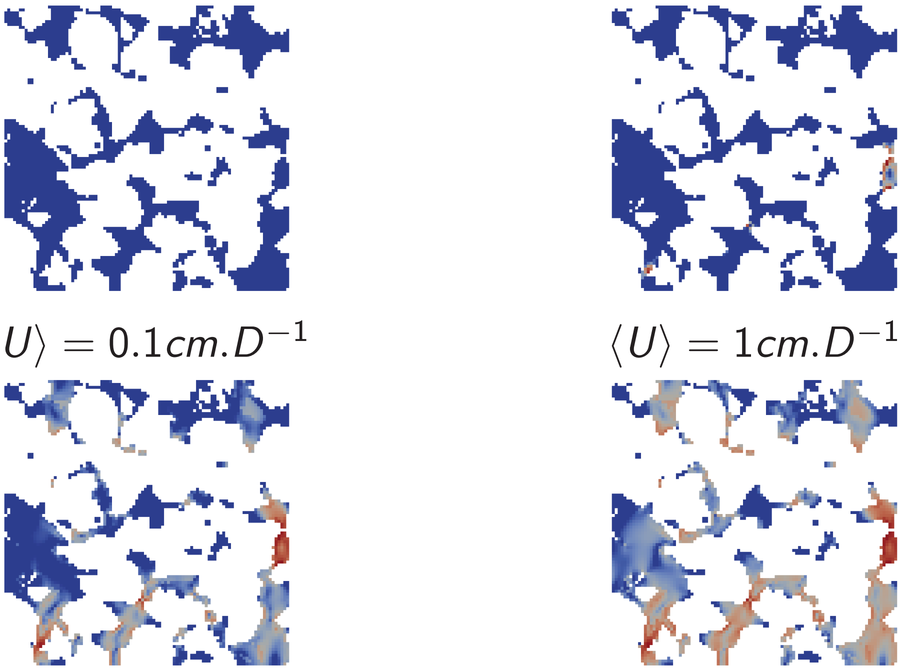


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing n and varying $\dot{\gamma}_c$.

Numerical results - Microscopic Phenomenology



$\langle U \rangle = 0.1cm.D^{-1}$ $\langle U \rangle = 1cm.D^{-1}$

$\langle U \rangle = 8cm.D^{-1}$ $\langle U \rangle = 22cm.D^{-1}$

Fig: Viscosity fields at different $\langle U \rangle$ for C1 case.

The non-Newtonian phenomena start in the pore throats and then extend in the larger pore (lower shear rate).

Numerical results - Microscopic Phenomenology

- Identify a critical pore throat volume with PDF.

Media	k_0	ϕ	ϕ_{PT}
A1	$1.1\,10^4$	0.72	0.175
A2	$1.3\,10^4$	0.75	0.252
P1	33	0.35	0.085
P2	46	0.44	0.10
B1	1.92	0.18	0.025
B2	0.82	0.17	0.022
C1	0.27	0.13	0.010
C2	0.48	0.14	0.014

Tab: Medium description (k_0 in Darcy unit)

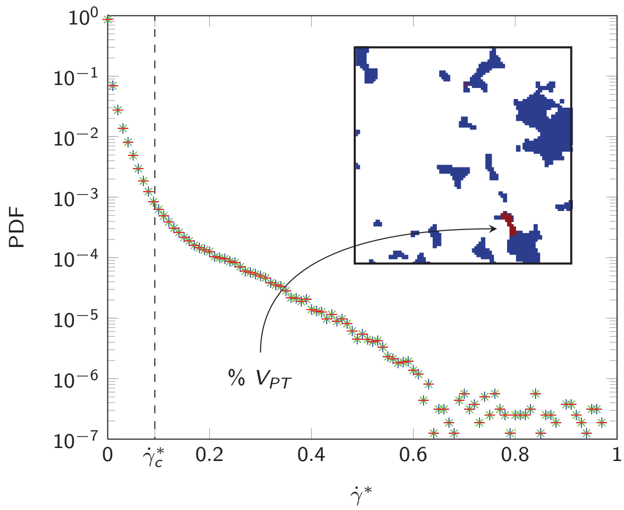


Fig: PDF of $\dot{\gamma}^*$ at $\mathcal{U}^* = 1$ for media C1.
Legend : + for $\dot{\gamma}_c = 10^0 s^{-1}$, × for $\dot{\gamma}_c = 10^1 s^{-1}$, — for $\dot{\gamma}_c = 10^2 s^{-1}$

Transition's model

- Our goal: predict $\langle U_c \rangle = \phi \times \dot{\gamma}_c \ell_{eff}$.
- Equivalent to: predict ℓ_{eff}.
- Validation by comparison between the model and $\langle U_c \rangle$ calculation (cross-over method).

Model for ℓ_{eff} :

- Use of $\sqrt{k_0}$. For Newtonian fluids, $\sqrt{k_0}$ is a pure topological parameter (even if PDE are needed). We have tried: $\sqrt{8k_0/\phi}$, $\sqrt{32k_0/\phi}$, $\sqrt{k_0/\phi}$, $\sqrt{k_0}$.
- Use of Kozeny-Carman formulation and equivalent diameter, Kozeny 1927; Plessis et al. 1994; Sadowski 1963.
- Use of volume or surface of the medium (V_{part}, V_{medium}, S_{part}), Li et al. 2011; Ozahi et al. 2008.

Best results using simply $\ell_{eff} = \sqrt{k_0}$. Leading to:

$$\langle U_c \rangle = \phi \dot{\gamma}_c \sqrt{k_0}. \tag{3}$$

Transition's model

Is $\ell_{eff} = \sqrt{k_0}$ so surprising?

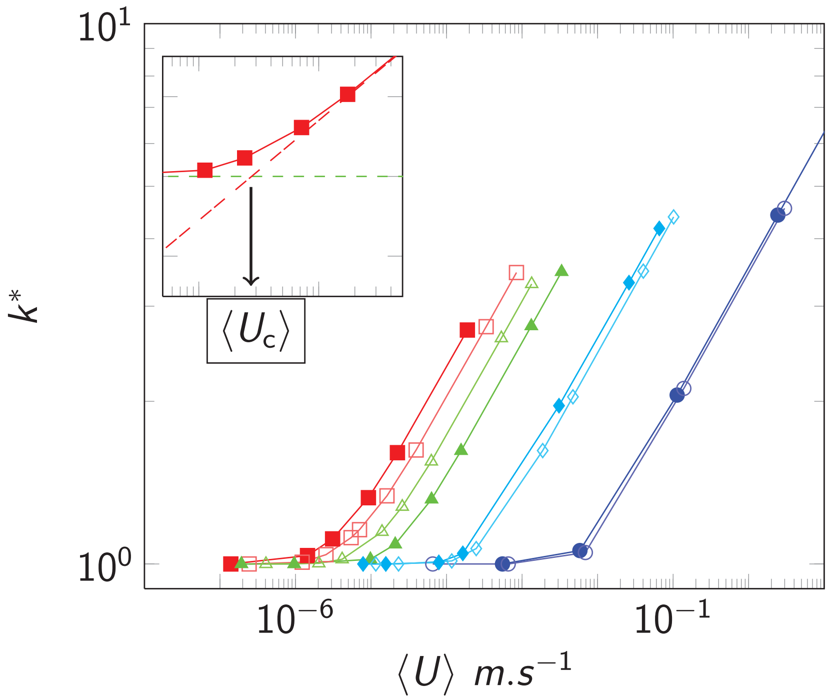
$$\dot{\gamma}_{eq} = \alpha \frac{4\left(\langle U \rangle / \phi\right)}{\sqrt{8 k_0 / \phi}} \iff \langle U_c \rangle = \frac{1}{\sqrt{2\phi\alpha}} \times \phi \dot{\gamma}_c \sqrt{k_0} \tag{4}$$

This would mean that without complex physical phenomena, $\ell_{eff} = \sqrt{k_0}$ is a good estimation for the ℓ_{eff}.

Ref erence	Medium	$\frac{1}{\sqrt{2\phi\alpha}}$
Lecourtier et al. 1984	P1	0.71
Chauveteau 1982	P1	0.87
Chauveteau 1982	C	0.52
Fletcher et al. 1991	C	0.46

Tab: Comparison with data found in literature

Full model



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Medium: A1, A2, B1, B2, C1, C2, P1, P2

Full model

- Relevant dimensionless non-Newtonian number, $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle} = \frac{\langle U \rangle}{\phi \times \dot{\gamma}_c \sqrt{k_0}}$

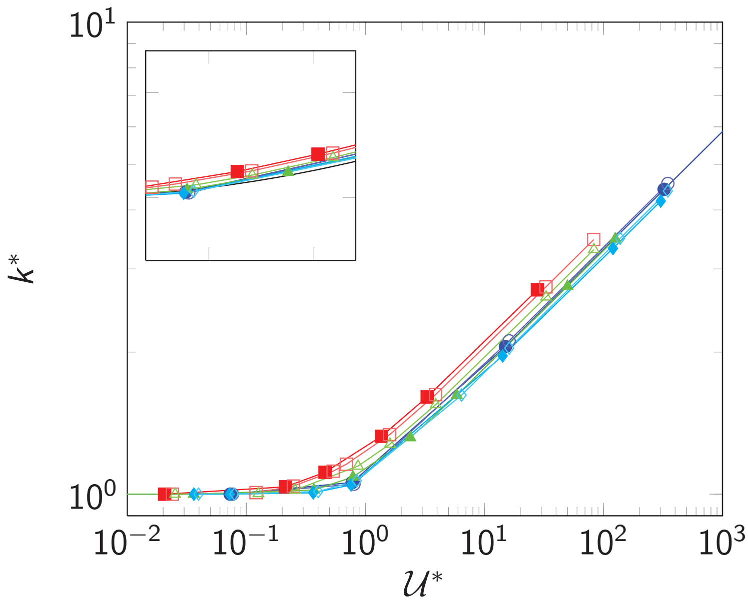

Fig: k^* versus $\mathcal{U}^*$. A1, A2, B1, B2, C1, C2, P1, P2

Conclusions & Applications

- Studying cut-off phenomena due to non-Newtonian fluid through porous media.
- Model the transition using rheological and topological parameters, $\dot{\gamma}_c$ and ℓ_{eff}.
- Definition of a dimensionless non-Newtonian number $\mathcal{U}^*$, which characterizes the regime.

Potential applications,

- use in core-flood experiments,
- estimation of critical distances characterizing the regime transition in petroleum and environmental engineering.

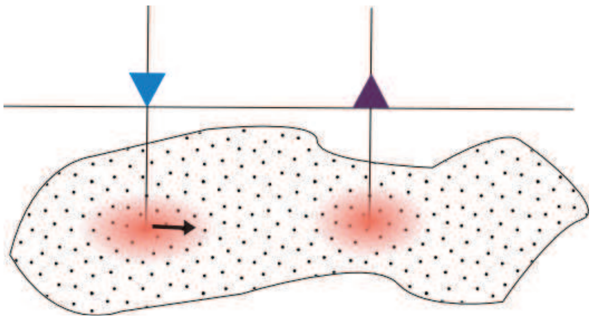

Fig: $\langle U_c \rangle \iff R_c = 50m$

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Thanks you for your attention. Any question is welcomed :)